LCA Case Studies

Life Cycle Assessment of Bio-ethanol Derived from Cellulose

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DOI: http://dx.doi.org/10.1065/lca2003.03.109

Abstract

Objective, Scope, Background. A comprehensive Life Cycle Assessment was conducted on bio-ethanol produced using a new process that converts cellulosic biomass by enzymatic hydrolysis. Options for sourcing the feedstock either from agricultural and wood waste, or, if the demand for bio-ethanol is sufficient, from cultivation are examined. The main focus of the analysis was to determine its potential for reducing greenhouse gas emissions in a 10% blend of this bio-ethanol with gasoline (E10) as a transportation fuel.

Methods. SimaPro 4.0 was used as the analysis tool, which allowed a range of other environmental impacts also to be examined to assess the overall relative performance to gasoline alone. All impacts were assigned to the fuel because of uncertainties in markets for the by-products. This LCA therefore represents a worst case scenario.

Results, Conclusion. It is shown that E10 gives an improved environmental performance in some impact categories, including greenhouse gas emissions, but has inferior performances in others. Whether the potential benefits of the bio-ethanol blend to reduce greenhouse gas emissions will be realized is shown to be particularly sensitive to the source of energy used to produce the process steam required to break down the cellulose to produce sugars and to distil the final product. One key area where improvements in environmental performance might be derived is in enzyme production.

Recommendations and Outlook. The LCA profile helps to highlight those areas where positive and negative environmental impacts can be expected. Technological innovation can be directed accordingly to preserve the benefits while minimizing the negative impacts as development progresses to commercial scales.

Keywords: Bio-ethanol; bio-fuel; biomass; cellulose bio-ethanol; enzymatic hydrolysis; ethanol; LCA; life cycle analysis; life cycle assessment; life cycle engineering

Introduction

Ethanol has been viewed as an alternative to gasoline, and has been used as a transportation fuel in a number of countries. In Canada, the use of bio-ethanol in this context is one of the important measures being considered to help meet the commitment to reduce greenhouse gas emissions. Iogen Corporation, an Ottawa-based biotechnology company, has constructed a pilot plant to demonstrate the viability of producing bio-ethanol on a commercial scale from wood and agricultural waste. The process (**Fig. 1**) uses enzymatic hydrolysis to break down the cellulose from waste wood, straw and other agricultural wastes to make sugars. These sugars are fermented to produce ethanol, which is then purified through distillation. The intent of the present study is to perform a quantitative analysis of the potential environmental benefits and limitations of using bio-ethanol as a transportation fuel. In particular, the analysis compares the life-cycle effects of gasoline, blended with 10% bio-ethanol produced by enzymatic hydrolysis (E10), with those of unblended gasoline.

The commercial software SimaPro 4.0 (http://www.pre.nl/simapro/) was used to conduct the LCA. The relative contributions of the different parts of the ethanol-blended fuel production cycle to ten environmental impact categories – greenhouse effect, acidification, eutrophication, winter smog,

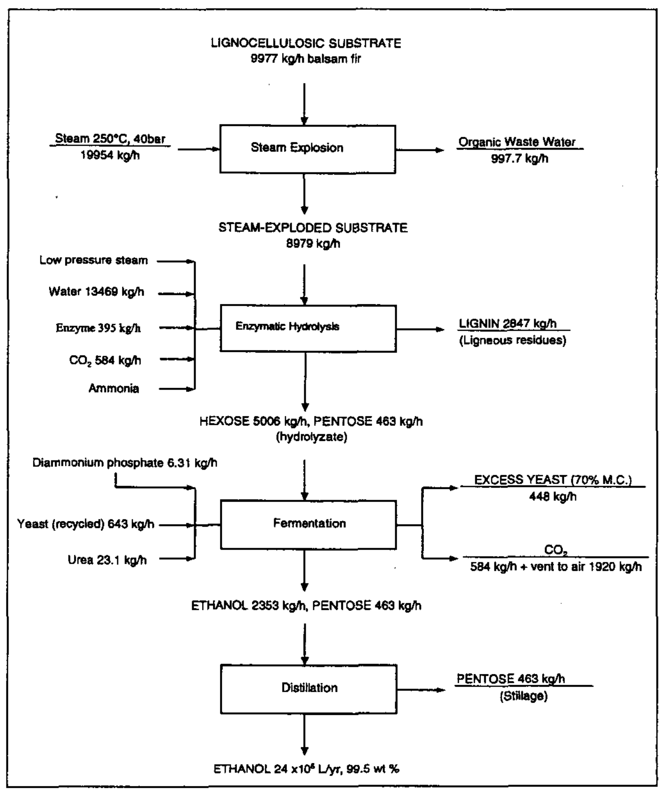

Fig. 1: The mass flow rates of a 25 ML/yr enzymatic hydrolysis ethanol plant

summer smog, carcinogenic substances, heavy metals, ozone layer depletion, pesticides, and solid wastes – were determined. The study also reveals those components of the life cycle that are the most demanding with respect to energy consumption and usage of material resources. This provides a comprehensive environmental picture of the potential benefits and impacts of substituting gasoline with bio-ethanol/gasoline blend and highlights specific areas where further technological development could yield environmental improvements. These insights are important to both researchers of the technology and policy makers.

1 Life Cycle Assessment

1.1 Ethanol fuel and functional unit

As a vehicle fuel, ethanol is mainly used in one of two ways [1,2]. The first one is blended with gasoline, typically 5 to 20 percent by volume, for use in existing vehicles with no engine modifications. The second is to use the ethanol, almost in its pure form (85 to 100%), in vehicles with specifically modified engines. In this study, ethanol is assumed to be used as a mixture of 10% ethanol and 90% gasoline by volume (termed here E10) on new vehicles with no engine modifications.

The functional unit chosen is to compare the life cycle flows on the basis of one-kilometer distance driven by new passenger cars.

Under these conditions, the amount of fuel required for travelling 1 km is calculated to be 62.4 g and 61.94 g for E10 and gasoline, respectively. This is based on fuel economy of 11.9 kilometer per litre (original 28 miles/gallon, cited from the US Energy Information Administration in [3]). Fuel economy is assumed to be the same for E10 and gasoline, although, as reported in [3], in-use experience has indicated that E10 may have approximately a 1% fuel economy penalty.

1.2 Scenarios and allocation

The raw biomass material for ethanol production may either come from agricultural and forest wood wastes or, if the product demand is sufficiently large, from cultivated feedstock (assumed to be hay production in Ontario). The process steam required for breaking down the substrate and subsequent hydrolysis, fermentation and distillation may be provided through conventional fossil/electricity sources or through the use of waste biomass. Again, if product demand is sufficiently large, there may be an incentive to divert the waste biomass used as a process energy source for use as feedstock and to substitute an alternative, possibly fossil-based, source. To examine the consequences of these options, four scenarios were analyzed. These are shown in Table 1.

Table 1: Four scenarios of bio-ethanol fuel studied

Case	Feedstock	Process Energy Source
E10-A	**Cultivated**	**Fossil Electric Grid**
E10-B	Waste Biomass	Fossil Electric Grid
E10-C	**Cultivated**	**Waste Biomass (lignin, etc.)**
E10-D	Waste Biomass	Waste Biomass (lignin, etc.)

There are a number of potential by-products associated with bio-ethanol production, including lignin, pentose sugars and animal feed products. Besides being used for ethanol production, pentose sugars can be concentrated to 48% syrup, which can then be sold as animal feed molasses or be used as substrate for yeast production. They can also be used to produce a methane-rich biogas through anaerobic digestion, or be converted to furfural, which is a useful chemical intermediate in some industries. Any excess yeast not required for fermentation can be dried to about 10% moisture content (M.C.) and sold as fodder yeast. Lignin can be sold for lignin chemicals, in the area of phenolic substitution, or can be used to produce steam or electricity for plant use, or can be sold directly as fuel [4]. However, because the bio-ethanol production process is still at the pilot-plant stage, this LCA has treated the by-products as if they had no value by allocating 100% of the inputs to the main product – bio-ethanol. This is a conservative estimate of the environmental loads attributable to bio-ethanol, but it can be justifiable given that sufficient markets for the by-products may not exist at commercial scale production volumes. An LCA with significant by-product allocation would only be valid to the extent that the bio-ethanol producer develops and maintains these by-product markets.

1.3 System boundary and data sources

Fig. 2 shows the major operations included within the boundary of the bio-ethanol system for conducting the life cycle inventory (LCI) calculations. Data gaps resulting from commercial confidentiality or general data unavailability are filled by making a variety of assumptions as noted below. To protect intellectual property rights, industry average data are generally used, preferring Ontario averages wherever these exist. Production and end-use combustion technologies reflect current best-available performance. Data in the study were collected from a variety of sources including research reports, experts, literature, and recent environmental reports of the world's leading companies in related fields. Some data were taken directly from the SimaPro 4.0 database.

Not included are the manufacturing and materials of construction of capital equipment and facilities used for ethanol production and automobiles, or the packaging system for ethanol distribution.

1.4 Key assumptions

In this study, the transportation of materials and products is assumed to be by road, using medium-heavy diesel trucks with a load of 6.4 to 15 tonnes. The transportation distance is assumed to be 150 km (300 km both ways) unless specified otherwise. In the SimaPro 4.0 database, the LCI data associated with medium-heavy petro-diesel truck transportation are related to average emission and fuel consumption for transporting 13.8 tonne-km in the Netherlands. This is considered to be representative of medium-heavy diesel truck performances for the purposes of the study reported here. Subsequently, it was found that this would not represent

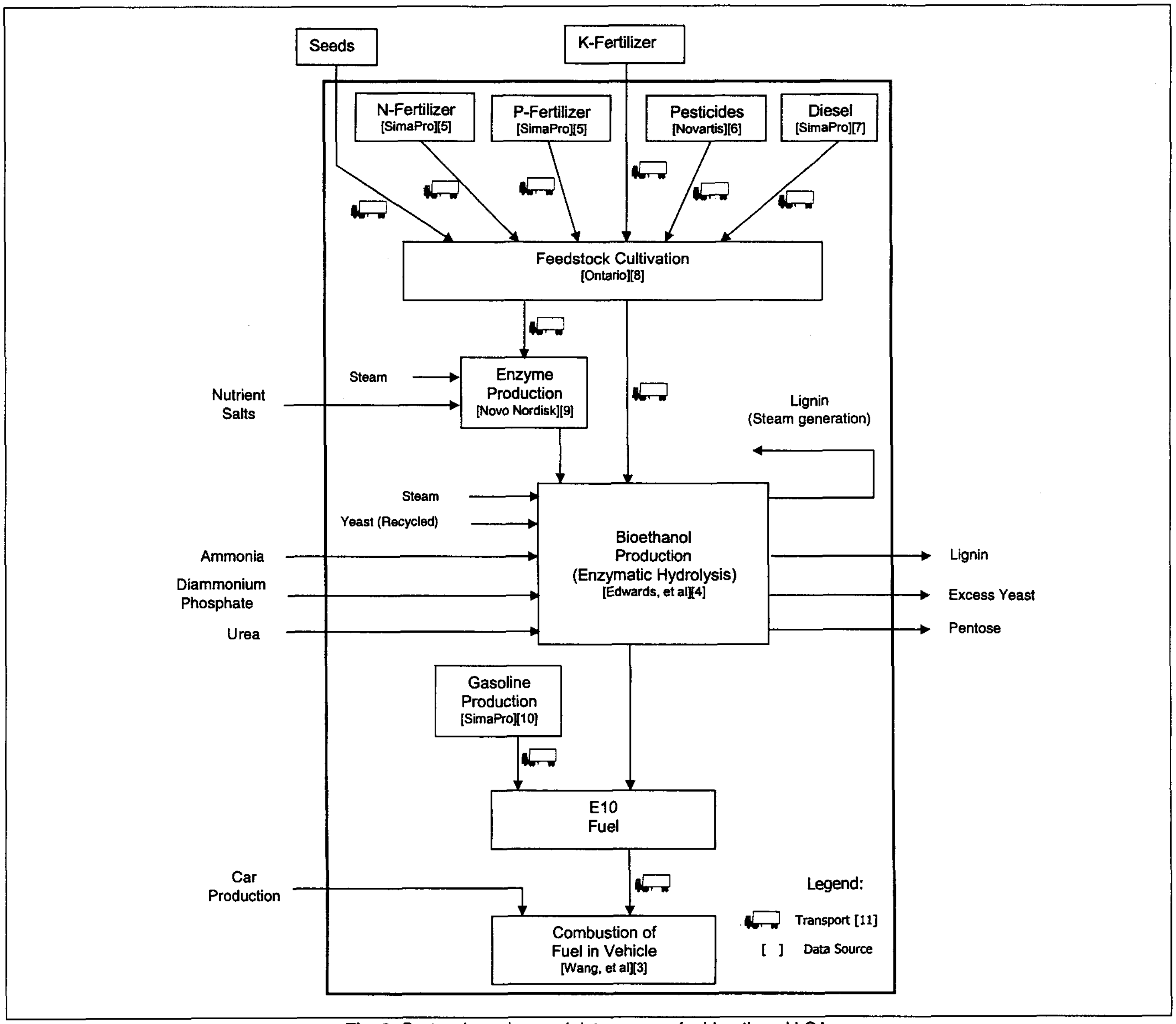

Fig. 2: System boundary and data sources for bio-ethanol LCA

precisely the LCI data for petro-diesel in Canada. In Canada, the petro-diesel is a blend sourced from heavy oil, off-shore oil and so-called 'synthetic' oil (derived from oil sands). This blend varies across Canada. However, since this only affects the transportation component of the analysis, it is not considered significant.

The manufacturing of gasoline and of E10 has been considered at a comparable level of detail. The LCI data associated with petroleum gasoline manufacturing have been taken directly from the SimaPro 4.0 database, whereas data for the manufacture of bio-ethanol have been derived from Canadian sources. Although the LCI for gasoline sourced in Canada differs from that in SimaPro, since E10 fuel contains 90% gasoline and the comparisons reported here are between 100% gasoline and E10, any regional differences in LCI tend to cancel out. It would be significant if the absolute, rather than relative, numbers were used in drawing the conclusions.

For greenhouse gas emissions, only fossil-based CO_2 emission is counted; bio-based CO_2 is treated as zero (i.e. carbon neutral), assuming this balances with sequestrated carbon over the long term.

2 Results and Discussions

In the presentation of the findings that follows, it would be useful to be able to put error bars or confidence bounds on the results to confirm that the differences observed between the scenarios is significant. This can be done through sensitivity analysis, but has not been conducted on this study as this is cumbersome using SimaPro. However, it is important to point out that the LCI for gasoline is common to all scenarios, the only difference being that for gasoline alone it represents 100% of the emissions, while for E10 it is 90%. Thus, the differences observed between the scenarios are due almost entirely to the effect of 10% bio-ethanol replacing 10% gasoline.

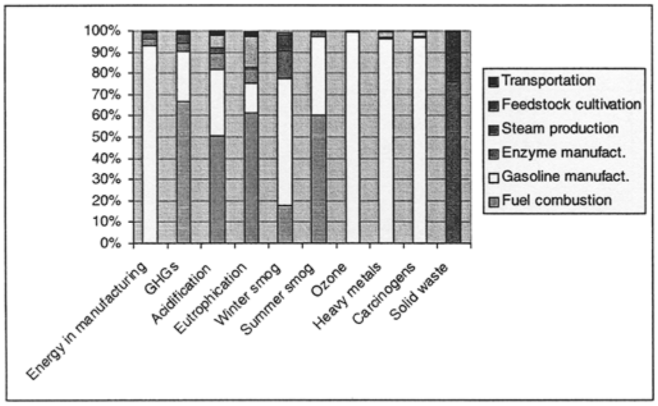

Fig. 3: Characterization result – distribution of life-cycle environmental performance of E10-a

The LCA results associated with scenario E10-a are presented in **Fig.** 3 for ten impact categories. Per km driven, they are:

- greenhouse gases: equivalent to 0.256 kg CO_2 (the CO_2 emission of biomass origin is treated as zero)
- acidifying gases: equivalent to 1.88 g SO_2
- eutrophication: equivalent to 0.278 g PO_4
- winter smog: equivalent to 0.689 g dust
- summer smog: equivalent to 1.08 g C_2H_4
- ozone depleting gases: equivalent to 0.318 mg CFC11
- heavy metals: equivalent to 0.654 mg Pb
- carcinogenics: equivalent to 0.00608 mg benzo[a]pyrene
- solid wastes: 0.719 g
- energy consumption: 5.1 MJ.

For scenario E10-a, most of the energy consumption and emissions originate from the combustion of the fuel and the production of gasoline. This is not unexpected, since 90% of E10 is made up of gasoline. Similarly, most of the emissions of ozone depletion substances, heavy metals, and carcinogenic substances originate from gasoline manufacturing.

For bio-ethanol production, Fig. 3 indicates that enzyme manufacturing, steam production, and transportation are the main hot spots in terms of most impact categories, including energy consumption, greenhouse gas emissions, acidification, eutrophication, winter smog, and summer smog. Feedstock cultivation is also a major contributor to acidification, eutrophication, heavy metals, and carcinogenic substances. It also involves land use and bio-diversity issues, which, while critical, cannot be examined using current LCA methods.

Fig. 4 compares the environmental performance of E10 fuel with petroleum gasoline for all four scenarios. It can be seen that E10 consumes less energy than gasoline manufacturing under all conditions. The method of producing process energy seems more influential than the source of feedstock. This arises because in the LCA for electricity generation, fuel extraction and fuel processing are both energy consuming. In contrast, bio-fuels for process energy made from biomass such as straw, wood chips and lignin, demand less energy for extraction and processing.

From **Fig.** 5, it can be seen that the source of energy for process steam generation is critical for determining which fuel, gasoline or E10, is cleaner in terms of greenhouse gas emissions. If bio-fuel has been used to generate steam for breaking down the feedstock, E10 fuel will produce less greenhouse gases than traditional gasoline. On the other hand, if fossil-based electricity has been used in ethanol production, gasoline seems to be more climate change friendly. The greenhouse gas contribution from feedstock cultivation is relatively small. Here, the emissions are due mostly to N_2O from the cultivation step, and methane, fossil CO_2, etc. from the production of fertilizers and pesticides.

	E10-a	E10-b	E10-c	E10-d
Energy in manufacturing	+	+	++	++
GHGs	-	-	+	+
Acidification	--	-	--	-
Eutrophication	--	-	--	-
Winter smog	--	--	-	-
Summer smog	+	+	+	+
Ozone	++	++	++	++
Heavy metals	+	++	+	++
Carcinogens	---	o	---	o
Solids	--	--	--	--

--, -, 0, +, ++ : from 'more severe,' to 'same,' to 'less severe' environmental impact relative to gasoline

Fig. 4: Score sheet (reference to gasoline)

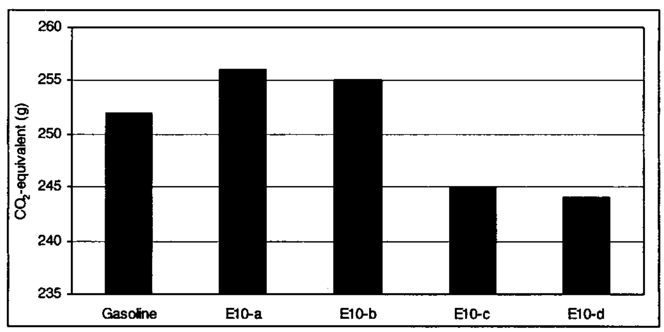

Fig. 5: Comparison of life-cycle greenhouse gas emissions for E10 fuels and gasoline per km driven

From Fig. 3, it is evident that bio-ethanol feedstock cultivation and enzyme manufacturing are the main contributors to eutrophication. For feedstock cultivation, the eutrophication impacts derive principally from the use of nutrients to enhance growth and from the production of fertilizers. For enzyme manufacturing, the main impacts come from feed production, since grains are needed for enzyme nutrition, and air and water emissions from the enzyme fermentation process.

For winter smog emissions, the relatively high contribution made by enzyme manufacturing is due to the emissions from its energy consumption and from the fermentation process. The relatively high contribution made by steam production is due to the combustion of the fuels. If the steam has been generated using bio-fuel for the purpose of breaking down the feedstock, winter smog emissions will be lower, since the emission of SO_2 from the combustion of bio-fuel will be lower than that of fossil fuels.

Fig. 4 indicates that the choice of fuel for steam generation and the source of feedstock makes no difference to summer smog emissions. This is because, for bio-ethanol manufacturing, summer smog emissions are mostly a result from enzyme production, as illustrated in Fig. 3. As one might expect, the main contribution to summer smog comes from fuel combustion in automobiles.

For solid waste emissions, the relatively high contribution by enzyme and fertilizer manufacturing is due primarily to the ash created to supply the process energy required for production.

For impacts on acidification, the contribution from enzyme manufacturing results from the emissions from its energy consumption, the agricultural activities for its raw material production, and fermentation process for its manufacturing. The contribution from feedstock cultivation is mainly due to the emissions from the nutrients in the cultivation step, the field operations and phosphate fertilizer manufacturing.

Although the total carcinogenic emissions are relatively low (0.07 mg benzo[a]pyrene-equivalent per functional unit), feedstock cultivation, mainly through pesticide manufacturing, is critical for determining whether bio-ethanol fuel gives more carcinogenic emissions than traditional gasoline. If the feedstock has been grown for the purpose of ethanol production, the carcinogenic emissions must be assigned to the bio-ethanol product, and the E10 will be less clean than gasoline alone. On the other hand, if waste wood or agricultural waste is used, this assignment will not be made and carcinogenic emissions for E10 will be much less and similar to those of gasoline.

3 Conclusions

Based on the assumptions and the data sources applied to this LCA study, the following conclusions can be drawn:

- Ethanol fuel as a blend in gasoline may help to reduce overall life-cycle greenhouse gas emissions only if the energy required to generate the process steam derives from biomass (e.g. lignin or bio-fuel) rather than fossil fuel for pretreatment of the feedstock.
- Replacing traditional gasoline by E10 fuel may save energy, lead to less summer smog and ozone depleting substances, and lower discharges of heavy metals. It may, however, result in increased eutrophication, acidification and winter smog, and generate more solid wastes.
- For bio-ethanol production, enzyme manufacturing, energy consumption for breaking down feedstock and haulage are the main sources of impact. It is in these areas that research can best be focussed to improve overall life cycle environmental performance.
- Feedstock cultivation contributes significantly to environmental impact in almost all categories, but particularly to acidification, eutrophication, heavy metals and carcinogenic substances. It can also be expected to give rise to biodiversity, landscape modification and land-use impacts. Use of biomass waste as a feedstock avoids these impacts.

4 Recommendations and Outlook

The Life Cycle Assessment conducted on bio-ethanol served to highlight the conditions and the level of benefits that can be derived from the use of bio-ethanol blended fuel for transportation. For example, it was found that any advantages of bio-ethanol over gasoline in the area of greenhouse gas reduction are highly sensitive to the source of process energy, and less sensitive to feedstock cultivation. As well, those parts of the life cycle and the specific areas where the use of bio-ethanol will lead to negative environmental impacts are identified. This helps to direct future research on technological innovation to ensure the environmental benefits of bio-ethanol will be preserved, while the limitations will be appropriately addressed, as the technology is scaled up for commercial exploitation.

Acknowledgements. The authors would like to thank Keith Raid of the Ontario Ministry of Agriculture and Rick Upfold of the University of Guelph for providing some of the data used in the study. The support of Jeff Passmore of Iogen Corporation for carrying out this study and reviewing this manuscript is also gratefully acknowledged.

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Received: June 5th, 2002
Accepted: March 28th, 2003
OnlineFirst: March 31st, 2003